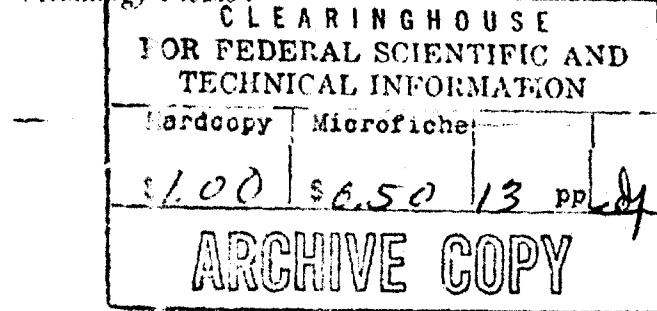


Fracture Toughness Characteristics of Some Titanium Alloys for Deep-Diving Vehicles

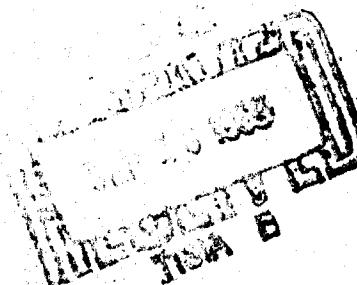
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Strength of Metals Branch

Metallurgy Division



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U.S. NAVAL RESEARCH LABORATORY
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The notch-fracture-toughness characteristics of a wide variety of titanium alloy plate are being investigated to provide alloy selection design and specification criteria for the use of titanium alloys as hull-materials for deep-diving submarines and other structural applications. The relationships between various standard and newly developed fracture-toughness tests have been established for one-inch-thick rolled plate, and the results from these tests have been correlated to the performance of the material in a structural prototype element test. A preliminary fracture diagram is presented for titanium which relates fracture toughness to strength level and the performance of the material in the structural prototype element test in the presence of flaws. The optimum materials trend line has been established, which indicates the maximum strength level for any given level of toughness. The fracture-toughness characteristics of a number of titanium alloys and their relationship to the optimum materials trend line have been delineated. Results of the alloy development and processing investigation provide useful guidelines for optimization of strength and toughness of titanium alloys.

INTRODUCTION

The role of the U.S. Naval Research Laboratory in the Navy's titanium program is that of (a) determining the fracture-toughness characteristics of titanium alloys using both standard and newly developed laboratory fracture-toughness tests, and (b) determining the significance of the values obtained from the fracture-toughness tests in providing engineering criteria to predict the service performance of the material in submarine hull structures. However, the information that has been developed is applicable to many other structural applications for titanium alloys as well.

The level of fracture toughness required in a titanium alloy for use in a hull structure depends upon a number of considerations which are related essentially to expected service loads the structure will experience during its projected life and to the effect of flaws on the ability of the materials to withstand service overloads without developing fast-running fractures under elastic loading conditions, *i.e.*, catastrophic failure. For example (Fig. 1), the size and complexity of the pressure hull of a combatant submarine dictates that the

hull material possess an ultrahigh (uh) level of fracture toughness, since there are numerous stress indeterminate points which in service may give rise to local high tensile loads.

Inspection techniques currently used preclude the detection of all flaws that develop during fabrication; new flaws (or cracks) may develop under low-cycle fatigue at design hard points or at fabrication defects after a short time in service. A high level of fracture toughness in a material is then characterized by the capability of withstanding plastic overloads in the presence of a flaw of reasonable size (largest size that could be missed in inspection or that would develop early in service) without running a fracture catastrophically. Only the low- and medium-strength alloys fall into this category. At the other extreme level of fracture toughness are the ultrahigh-strength alloys which have been successfully used in the aircraft and aerospace industry. These materials possess a low or medium level (L/MH) fracture toughness, in that they will run fractures under elastic loading conditions from very small flaws. The design details and load-stress calculations of the structures that have successfully used these materials have been precise enough so that in combination with "exact" inspection techniques, catastrophic failure has not been a major problem. It is expected that for smaller noncombatant-type vehicles, such as research submersibles and

NRL Problems M01-05 and R05-24A; Projects RR 007-01-46-5405, SR 007-01-02-0704, and WW 041. This is an interim report on one phase of the problem; work on other phases is continuing. Manuscript submitted February 11, 1965.

NOTE: This report was presented at the Metallurgical Society/AIME Session on "The Development and Status of Titanium Alloys for Deep-Diving Vehicles," Philadelphia, Pa., Oct. 1964.

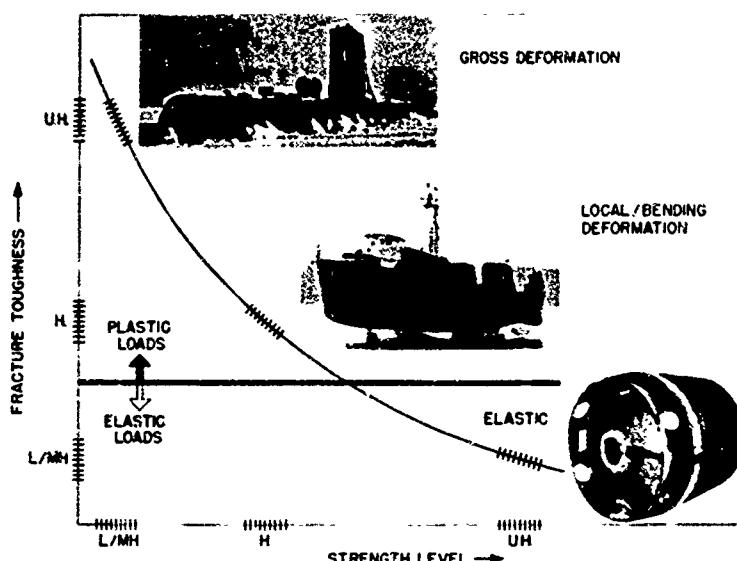


Fig. 1 — Levels of fracture toughness required for several different types of "naval structures"

hydrofoils, alloys should possess an intermediate or high (H) level of fracture toughness which is characterized by the ability to develop a small amount of plastic strain in the presence of a flaw without failure. This capability is found in relatively high-strength alloys.

For the present, linear elastic analysis based on fracture-mechanics concepts does not permit the development of information for the case of plastic overloads. However, it has been possible to develop guidelines by correlation of the performance of prototype structural elements with the results of both standard and new small-scale laboratory tests—for example, the Charpy V-notch test and the drop-weight test. The performance of the structural prototype elements can be related directly to the service performance of the materials.

The results obtained to date in this study on a wide spectrum of titanium alloys are presented along with brief descriptions of the test methods used. The use of this newly developed information in evaluating the effects of processing variables on a Ti-7Al-2Cb-1Ta alloy produced in a joint Bureau of Ships and Reactive Metals Inc. special processing program is also presented.

EXPERIMENTAL PROCEDURE

The fracture-toughness tests used were the standard Charpy V-notch test (C_v), the drop-weight tear test (DWTT), and the explosive tear

test (ETT). The C_v test is well known and needs no further explanation, except to say that the tests were conducted over a temperature range of -320°F to $+212^{\circ}\text{F}$ using a machine calibrated according to ASTM specifications. The DWTT is a small-scale laboratory test which provides a full-thickness fracture-toughness measurement of plate materials. The name of the test was derived from the original use of a falling-weight method of load application; the test setup is shown schematically in Fig. 2. The specimen size is $17 \times 5 \times 1$ in., and a brittle crack-starter weld is employed on the tension-loading edge of the specimen to provide a sharp, natural, fast-moving crack, which impinges into the material of interest. A bracketing technique requiring three or more specimens was used to determine the fracture-toughness energy to within a 250 to 500 ft-lb difference between incomplete break and complete fracture. In order to economize on test material and time spent in preparing specimens, a 5000-ft-lb pendulum impactor (Fig. 3) was designed and constructed to obtain a fracture-toughness measurement.

The ETT is a new method of full-thickness fracture-toughness evaluation that can be classified as a structural prototype element test. The test features are depicted in Fig. 4. These include:

1. A 12×18 in. restrained test section in a 22×25 in. plate that can be elastically or plastically

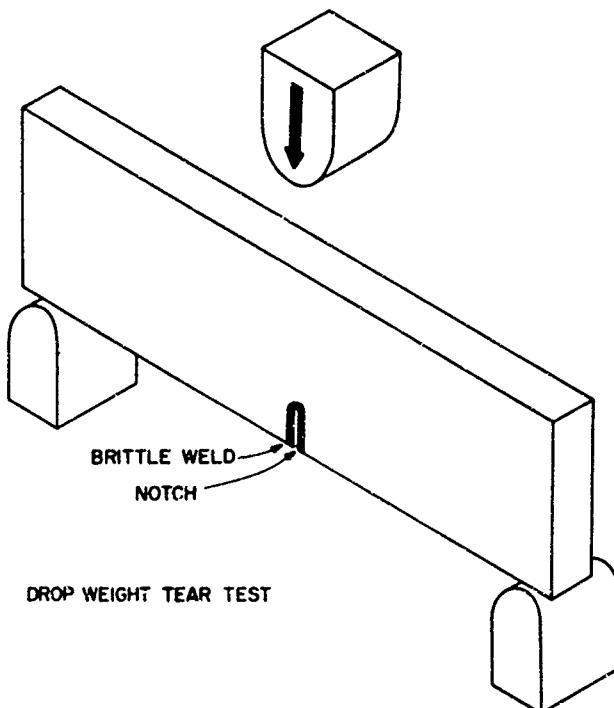


Fig. 2 — Schematic of the drop-weight tear test

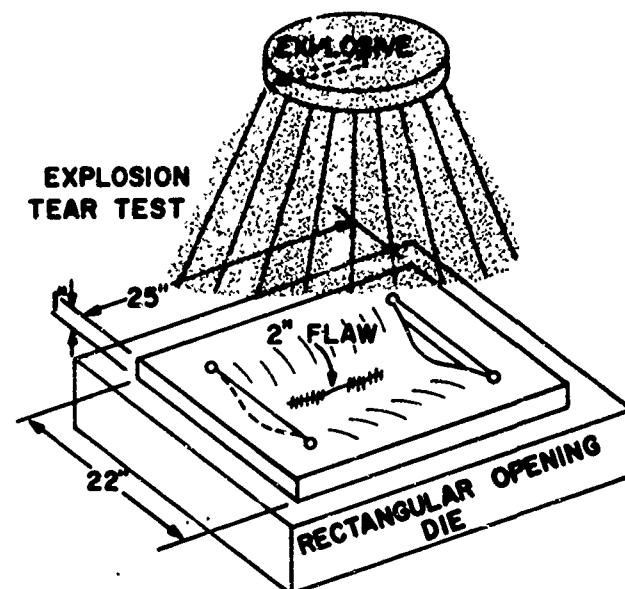


Fig. 4 — Schematic of explosion tear test

loaded to a cylindrical configuration under a high rate of loading, using explosive loading techniques.

2. A system of premarked grid lines for measurement of the strain-deformation pattern on the tension side of the plate.

3. A cracklike flaw for evaluation of fracture resistance when subjected to predetermined levels of elastic or plastic strain.

The ETT may be used to simulate a wide variety of service loadings in the presence of flaws of various selected dimensions. Initial investigations centered on the use of a 2T (2 in.) through-the-thickness crack as a practical flaw size of concern in large welded structures. Three levels of fracture toughness are indicated in Fig. 5. The relative level of toughness is indicated by the amount of plastic strain the plate can undergo with arrest of the fracture, originating from the sharp crack, within the test section.

The flaws in the DWTT specimens and in the ETT plates are provided by the brittle crack-starter weld, which is made by melt diffusion of an embrittling element, such as iron (iron or stainless steel wire), using electron-beam welding techniques. The amount of energy required to develop the crack in the brittle weld for the DWTT is below 300 ft-lb.

The spectrum of titanium alloys used to establish correlations between the laboratory tests and the structural prototype element test is shown in the following list.

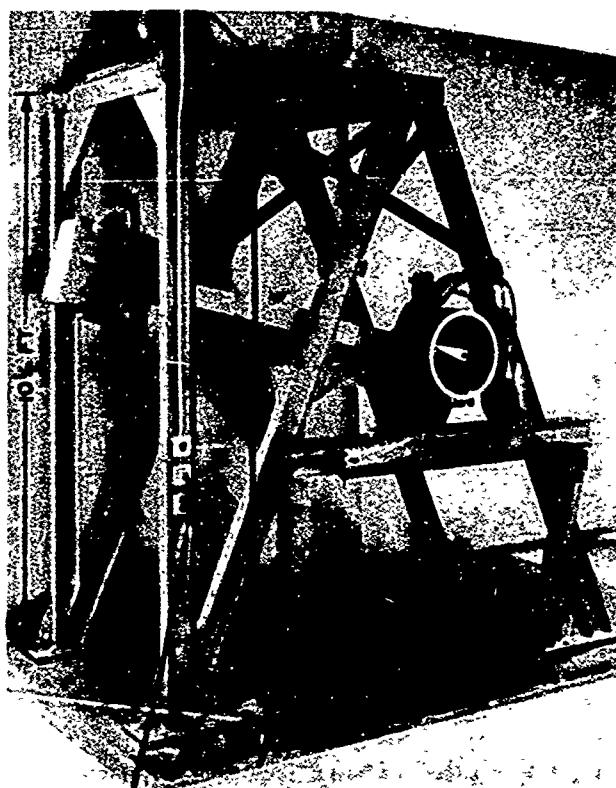


Fig. 3 — Impact machine of 5000 ft-lb capacity for testing 1- and 2-in.-thick plates of high-strength materials

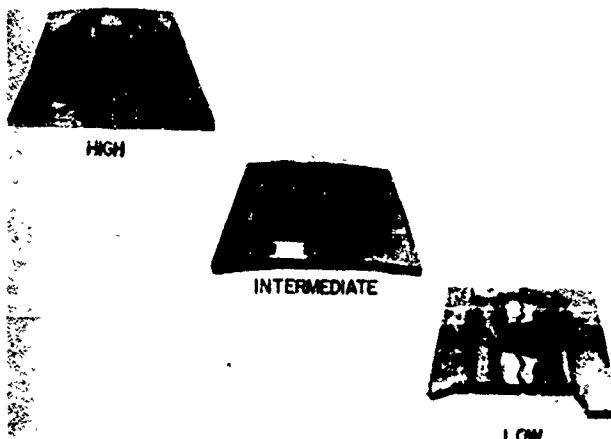


Fig. 5 — Explosion-tear-test plates showing high, intermediate, and low levels of fracture-toughness performance in titanium alloys

TITANIUM ALLOYS STUDIED IN THE CHARPY-V-NOTCH, DROP WEIGHT TEAR, AND EXPLOSION TEAR TESTS

ALPHA ALLOYS:

UNALLOYED TITANIUM
Ti-5Al-2.5Sn

NEAR-ALPHA ALLOYS:

Ti-7Al-2Cb-1Ta
Ti-8Al-2Cb-1Ta
Ti-6Al-4Zr-1V
Ti-6.5Al-5Zr-1V
Ti-6Al-2Sn-1Mo-1V
Ti-6Al-4Zr-2Mo

ALPHA AND BETA ALLOYS:

Ti-6Al-4V
Ti-8Al-1Mo-1V
Ti-6Al-4Sn-1V
Ti-6Al-2Mo
Ti-7Al-2Mo
Ti-7Al-2.5Mo
Ti-7Al-3Mo
Ti-7Al-3.5Mo
Ti-7Al-4Mo
Ti-6Al-6V-2.5Sn

BETA ALLOYS:

Ti-13V-11Cr-3Al

The alloys were commercially produced 1-in.-thick plates of approximately 0.15 wt-percent (minimum) and 0.08 wt-percent oxygen, standard and low interstitial grade respectively, as well as specially produced and processed 0.04 wt-percent oxygen 125-lb laboratory heats. This variation

in oxygen provided different combinations of strength and toughness. The alloys were tested in the annealed and heat-treated conditions to explore other combinations of strength and toughness. The laboratory fracture-toughness tests included the *RW* ("strong") and *WR* ("weak") orientations (1), *i.e.*, the effects of orientation with respect to the principal direction of rolling, and the ETT included only the *WR* orientation. Room-temperature tensile properties of the alloys were obtained using 0.313-in.-diameter specimens tested at a strain rate of 0.002 in./in./min.

TEST RELATIONSHIPS

Charpy V-Notch Energy Relationships to Yield Strength and Temperature

The temperature relation of C_v notch properties of the titanium alloys in different ranges of yield strength (YS) is shown in Fig. 6. As would normally be expected, the C_v energy decreases with decreasing temperature and increasing YS. These energies are represented as bands for different ranges of YS. Generally for each band the low YS values lie in the upper portion of the band, and the high YS values in the lower portion of the band. The individual C_v curves that make up the bands do not undergo

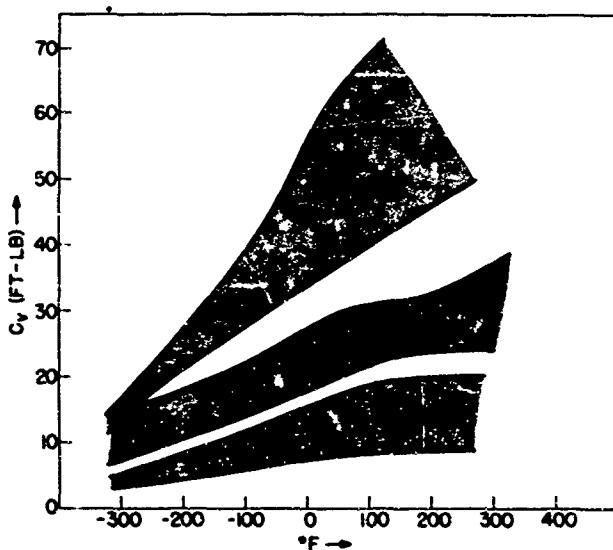


Fig. 6 — Relation of Charpy V-notch energy to temperature for different ranges of yield strength (ksi) in high-strength titanium alloy plate material

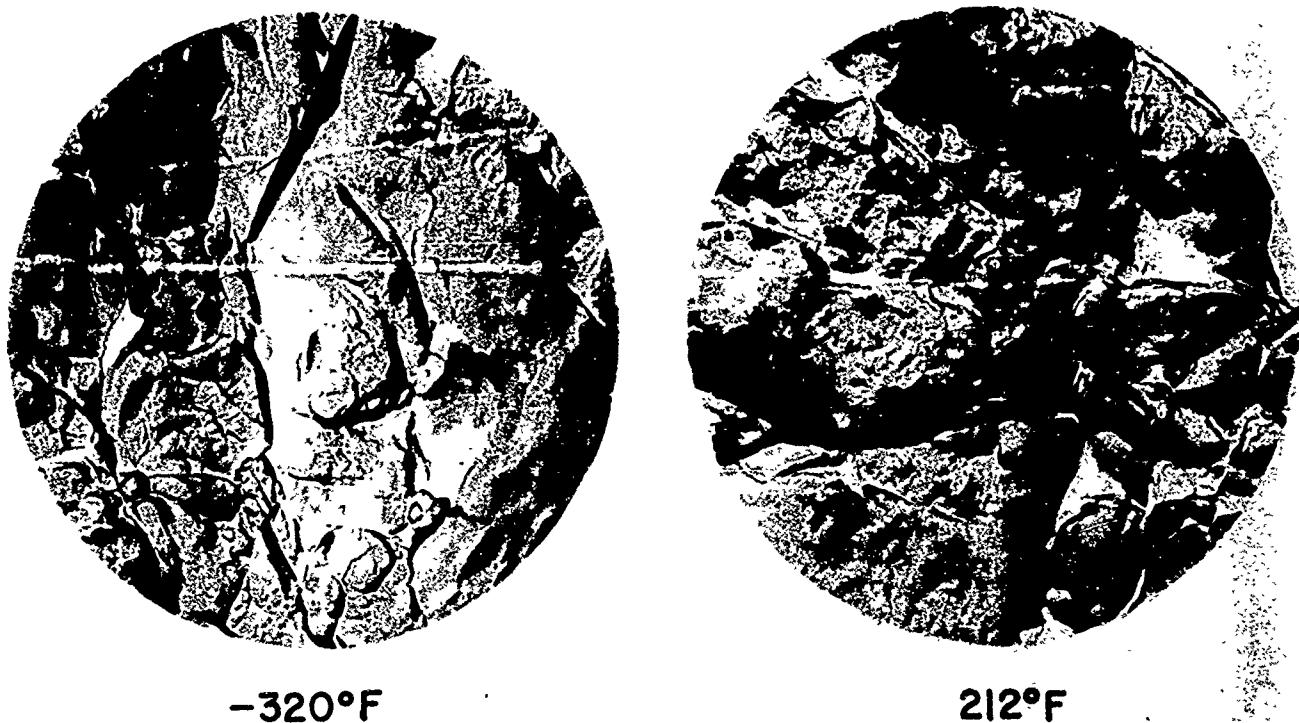


Fig. 7 — Electron microscope fractographs of a low interstitial Ti-6Al-4V alloy fracture surface, showing a dimpled rupture. Fracture surface generated at -320°F and $+212^{\circ}\text{F}$; 4000X.

a sharp transition over a narrow temperature range.

Fractographic studies of fracture surfaces of a number of these alloys with an electron microscope have shown that over the extremes of fracture toughness, temperature, and interstitial levels, the mode of fast fracture is dimpled rupture—a ductile mode of fracture (2). A typical example of the appearance of the fracture surface for these materials is shown in Fig. 7, the fractograph of a Ti-6Al-4V low interstitial alloy. The absence of a change in fast-fracture mode may explain the lack of an abrupt transition in the C_r curve as is usually seen for conventional structural steels.

Relation of Charpy V-Notch Energy with Drop-Weight Tear Energy

The relation between the C_r energy and DWTT energy at 30°F for a 1-in.-thick plate is shown in Fig. 8. The selection of this particular temperature to make this comparison is based on the intended use of this material. The lowest test temperature that a submerged hull structure could experience

is approximately 30°F . A band is defined by the data points; it is noted that above 2500 ft-lb DWTT energy, there is a reasonably direct correlation between the two tests. Below the 2500 ft-lb DWTT energy value, the C_r test shows a decreased sensitivity to differences in fracture toughness as compared to the DWTT. Unfortunately, this is also the region where most of the high-strength titanium alloys above 110 ksi YS lie.

Relation of Laboratory Tests with Explosion Tear Test

The significance of the DWTT energy values for the titanium alloys has been established by correlation with the performance in the ETT prototype element test. The preliminary correlation of these tests with the YS of the 1-in.-thick titanium alloy plate (Fig. 9) is termed the "fracture diagram for titanium." It is noted that a wide range of fracture toughness can be developed by different alloys of the same strength level. The curve delineated by the maximum levels of fracture toughness for given yield strengths has been designated the "optimum material trend line" (OMTL). This limiting curve establishes a

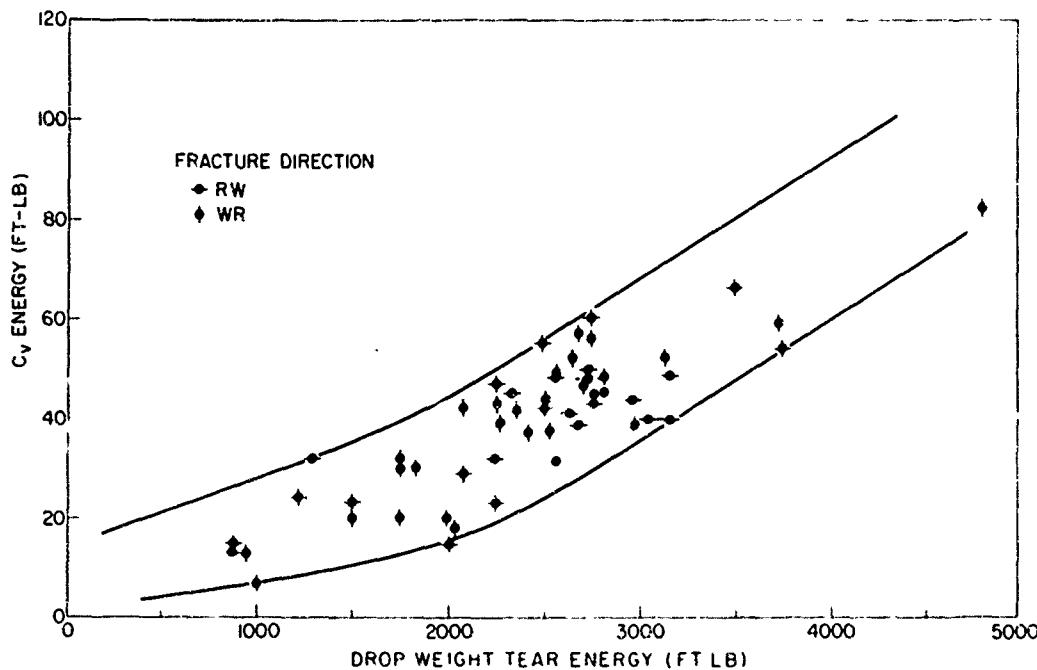


Fig. 8 — Relationship between Charpy V energy and drop-weight tear energy for 1-in.-thick titanium alloy plate

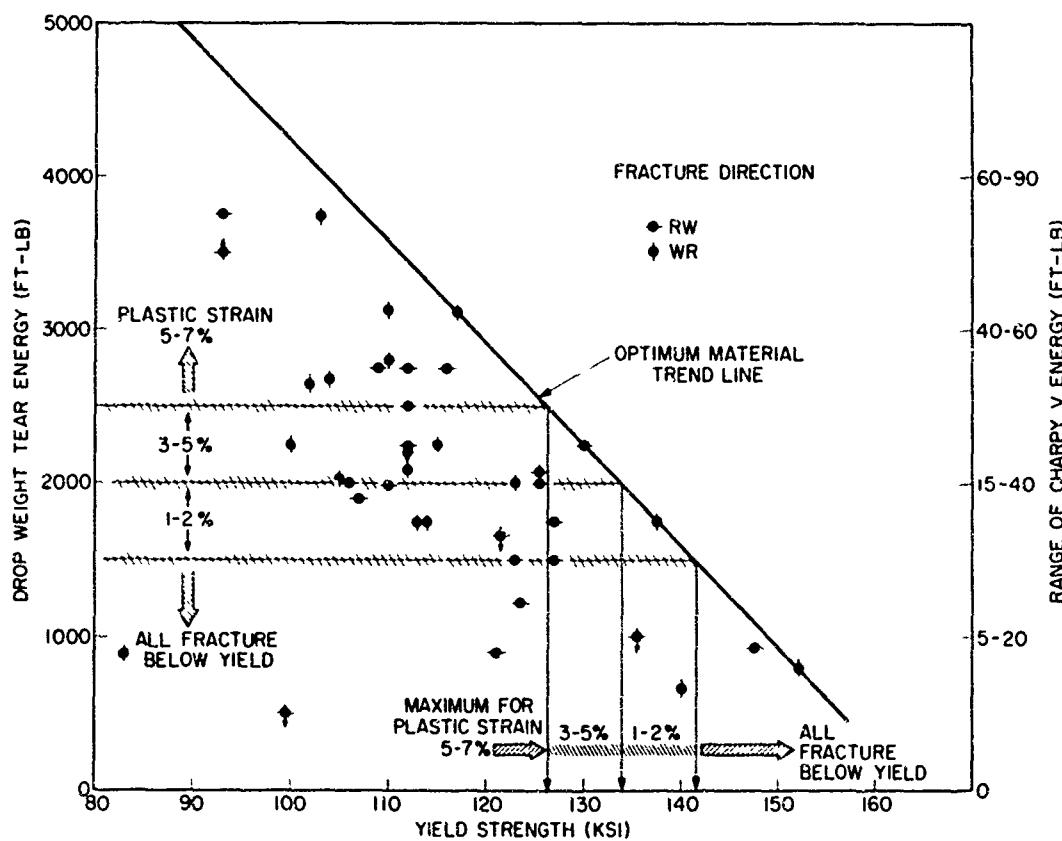


Fig. 9 — Relation of drop-weight tear energy and explosion-tear-test performance for 1-in.-thick titanium alloy plate containing 2-in.-flaws. The range of Charpy V energy for corresponding drop-weight tear-energy values is also indicated.

good reference point for evaluating alloys, for optimizing structural design, and for purchase specifications. Explosion tear tests of a limited number of specimens containing 2-in. flaws have tentatively established the plastic strain limits illustrated by the hatched lines. These limits indicate that materials having DWTT energy values below 1500 ft-lb will fracture under elastic loading conditions in the presence of the 2-in. flaw. Above 2500 ft-lb a high level of plastic loading (5 to 7 percent plastic strain) can be attained in the presence of the 2-in. flaw with limited propagation of the fracture. Between these extremes, intermediate levels of plastic loading can be attained in the presence of the subject flaw. The relationship also suggests that no materials over about 140 ksi YS are capable of withstanding plastic loading in the ETT in the presence of the 2-in. flaw without catastrophic failure. Titanium alloys up to about 125 ksi YS should be capable of withstanding a plastic strain of 5 to 7 percent with the development of a short

(arrested) fracture. Between these YS limits, lesser amounts of plastic strain may be applied with resulting restricted fracture. The range of C_r energy values is also indicated for the corresponding DWTT values.

DISCUSSION

Based upon these studies, an Interim Guide issued by the U.S. Marine Engineering Laboratory (3) has modified the previous 120 ksi YS, 21 ft-lb C_r at -80°F minimum specification requirements for titanium intended for submarine hull construction to a 105 ksi YS and 2000 ft-lb DWTT energy. This specification corresponds to an expected development of 3 to 5 percent plastic strain prior to fracture propagation in the ETT in the presence of a 2-in. cracklike flaw and a guaranteed 1 to 2 percent plastic strain.

The 1-in.-thick plate alloys that have been investigated which fall within these revised specifications are shown in Fig. 10. The data points

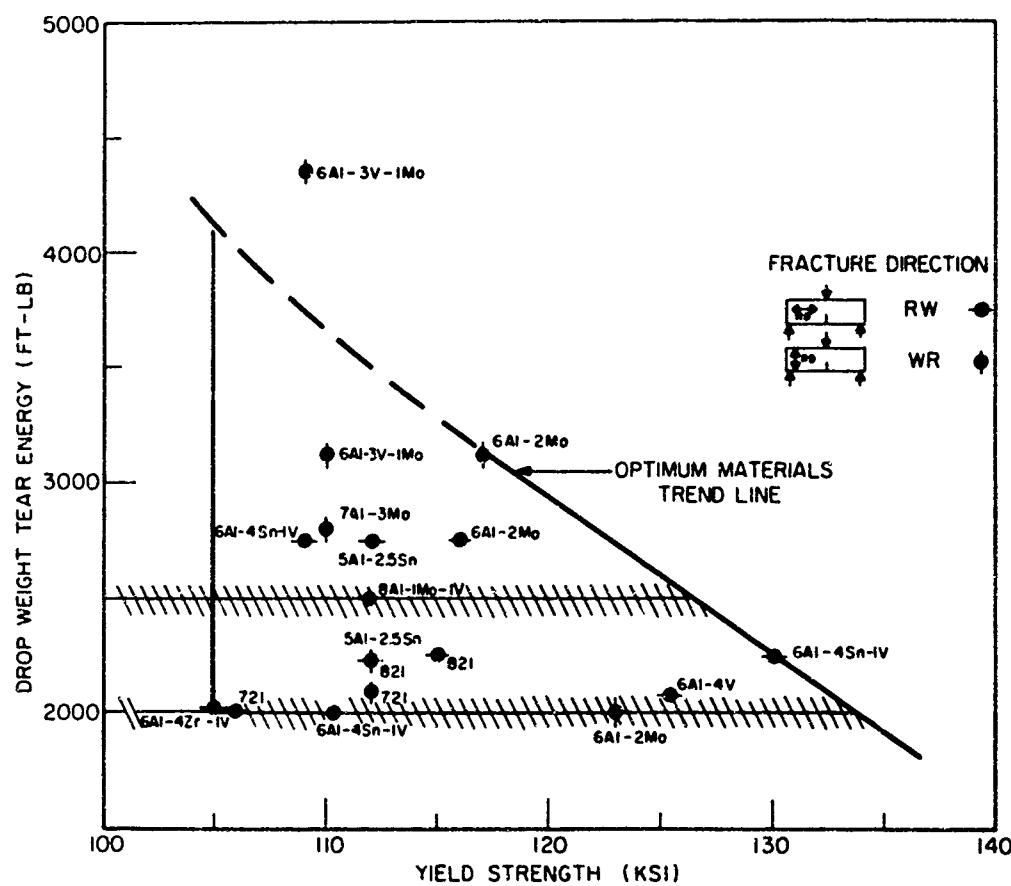


Fig. 10 — Portion of fracture-toughness diagram for titanium alloys, 1-in. plates, 2-in. flaws, showing variety of alloys that are within desirable limits for hull materials

were obtained in the hot-rolled condition and in various heat-treated conditions, depending upon the alloy, and, as can be seen, a number of alloys are represented. The remaining principal deciding factor on the usefulness of any of these alloys in the region of interest as a hull material is dependent upon the weldability of the material.

It is hopeful that the *OMTL* can be moved to higher levels of strength and fracture toughness through introduction of new alloys resulting from alloy development studies, through heat treatment, and through processing. An example of what possibly can be done through alloy development and heat treatment is the Ti-6Al-3V-1Mo. This alloy was made in the vacuum arc skull melting facilities at NRL in the form of a 65-lb vacuum arc remelt cast into a 4 × 7 × 12 in. copper chill mold, following which a one-half section of the billet was forged and rolled at NRL. The oxygen level is approximately 0.04 percent, and through heat treatment it has been possible to develop over 4300 ft-lb DWTT energy at a 109 ksi *YS* level. As seen in Fig. 10, these properties exceed the previously established *OMTL*. Scaling this alloy up to a large commercial heat would probably result in decreasing its toughness capabilities. However, the combination of strength and toughness of this alloy should fall near the *OMTL*.

The value of the DWTT as a laboratory fracture toughness test tool is demonstrated by its use in a study of processing variables on the mechanical properties of a Ti-7Al-2Cb-1Ta alloy being conducted by Reactive Metals Inc. under sponsorship of the U.S. Bureau of Ships. NRL is evaluating the plate material evolved in this study in the DWTT and ETT to provide guideline information on the full plate thickness strength-toughness combinations developed in relation to the *OMTL* for titanium. The average chemical composition as determined by the producer of the alloy is:

Element	Al	Cb	Ta	Fe	C	N ₂	O ₂
Weight-Percent	6.9	2.5	1.1	0.13	0.01	0.006	0.063

Plates nominally 1 in. thick were made by breaking the ingot down to slabs using three different forging techniques and then hot-

rolling. Also, forged billets of the same vacuum-melted ingot were extruded at 1700°F and 1900°F into 1 × 5 in. sheet bars of variable length using a 5500-ton press. Different annealing and aging temperatures were used on these materials, and DWTT energy was used to determine the effects of processing variables and heat treatment on the notch-fracture toughness properties. The results are shown in Fig. 11.

One of the processing procedures coupled with heat treatment for forged-and-rolled plate has produced material which approaches the estimated *OMTL* for titanium (forging process A). The extrusion process D produced material with properties which exceed the *OMTL* when tested in the "strong" direction (*RW*). However, the *OMTL* represents the "rolled plate" weak-direction properties, and on this basis the "weak" direction (*WR*) extrusion properties are considerably below the *OMTL* (only two specimens were tested in the *WR* orientation, and only one fell in the area of interest). The materials provided from this study have shown in general a better combination of strength and toughness over that seen in any of the previously produced Ti-7Al-2Cb-1Ta and Ti-8Al-2Cb-1Ta alloys investigated at NRL (Fig. 12).

A comparison of *C_r* and DWTT energy values determined at 32°F for the extruded materials is given in Fig. 13. Also included are the fracture surfaces generated in the DWTT, showing the difference in fracture texture related to extruding above and below the β *transus* and annealing above (specimens 3 and 4) and below (specimens 1 and 2) the β *transus*. The fact that the correspondence between the *C_r* and DWTT energies is poor is significant, in that the performance of the material can be predicted in the ETT from the DWTT results. This lack of correspondence between the two tests is the principal reason that little success has been obtained with the *C_r* test in making the same ETT performance predictions.

SUMMARY

The fracture-toughness characteristics of a spectrum of titanium alloys have been determined using small laboratory tests—the *C_r* test and the DWTT—the latter being a test which measures the full-thickness fracture-toughness properties.

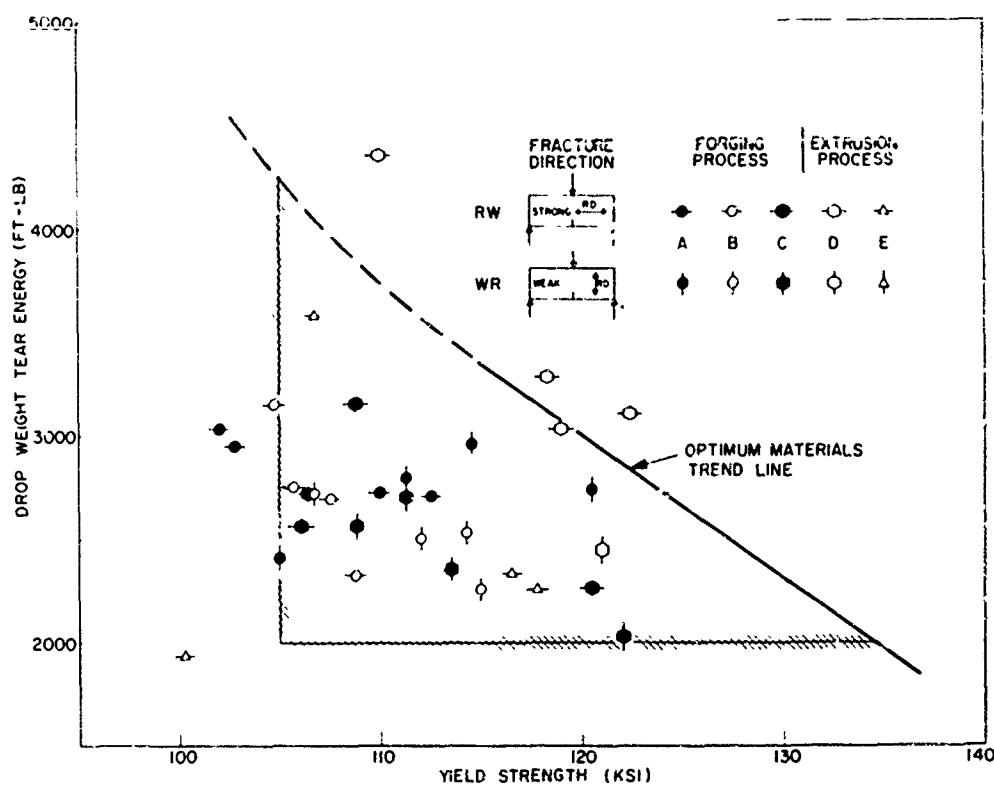


Fig. 11 — Results obtained with specially processed Ti-7Al-2Cb-1Ta alloy; optimum materials trend line established for forged-and-rolled plate material in earlier studies. The Navy zone of interest is defined by minimum-property lines at 105 ksi YS and 2000 ft-lb DWTT energy. Forging Process A: Forged on side; B: Upset forged; and C: Combination of A and B. Extrusion Process D: Extruded at 1700°F; and E: Extruded at 1900°F.

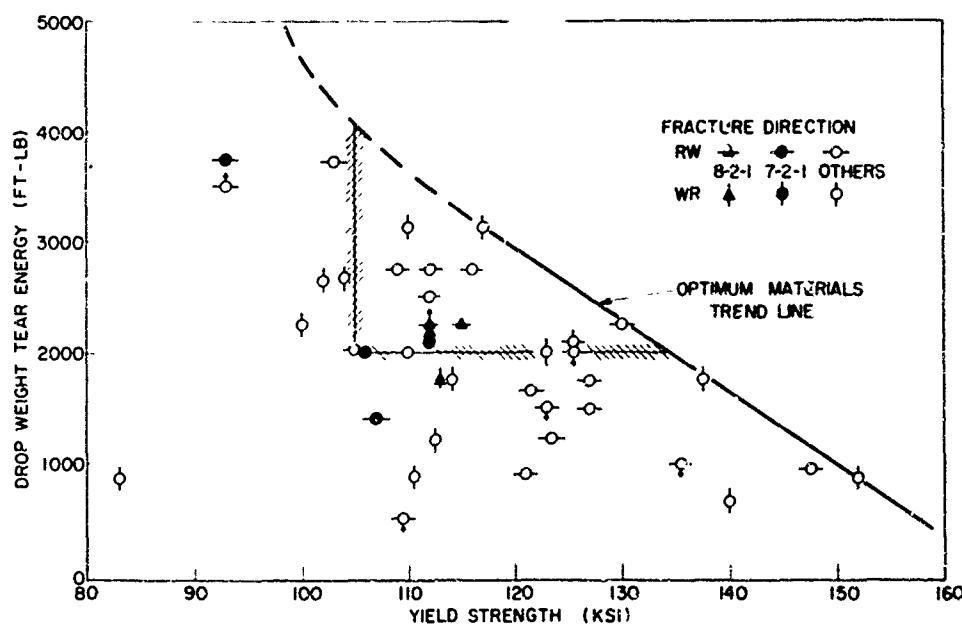


Fig. 12 — Fracture toughness properties of Ti-7Al-2Cb-1Ta and Ti-8Al-2Cb-1Ta alloys, 1-in. plate, investigated prior to special processing program; shows fracture-toughness properties relative to all other alloys investigated.

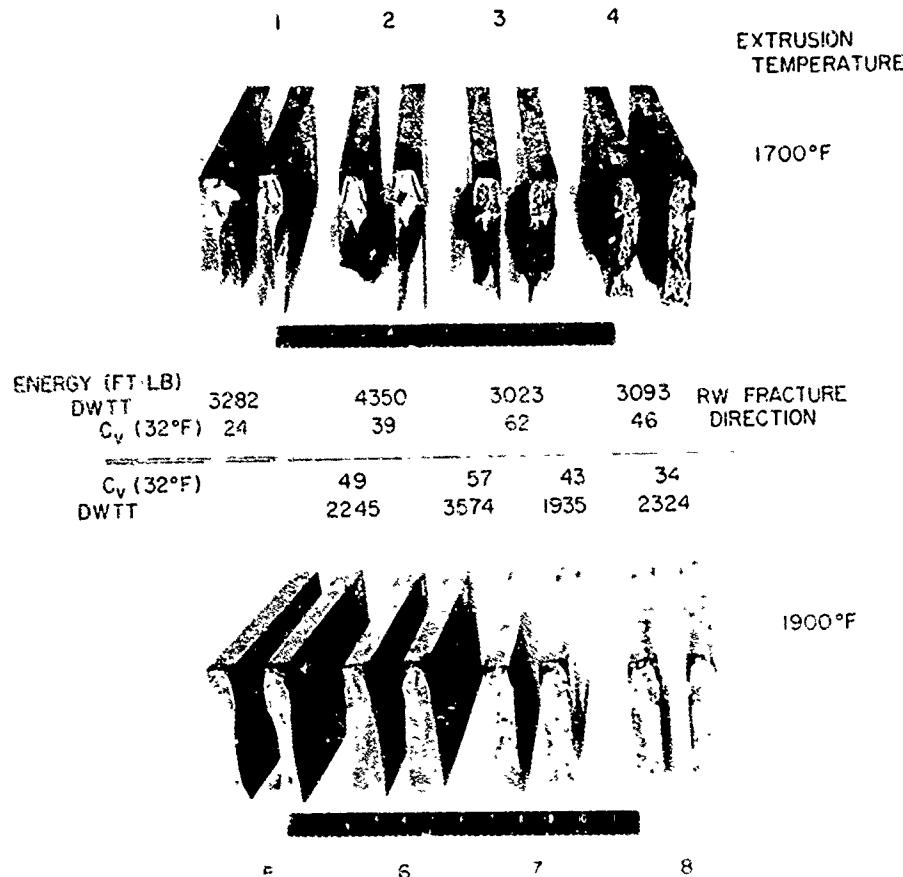


Fig. 13 - Extruded Ti-7Al-2Cb-1Ta drop-weight tear-test specimens showing fracture surface and corresponding drop-weight tear-test and Charpy V energy values.

The significance of the values obtained with the laboratory tests has been determined by correlation with the ETT, a full-thickness structural prototype element test, that incorporates a flaw of the acuity that would develop in fabrication and/or service and plastic overloads that may be expected in service. The results of these studies show that it is possible to predict the expected structural performance of the titanium plate and forgings from the DWTT energy values through correlation with the ETT. The relationships of the C_v test and the DWTT have also been established for these materials, and they show that the sensitivity of the C_v test in measuring fracture-toughness differences is significantly less than that of the DWTT for the strength levels of interest.

This study has shown that a number of titanium alloys can develop levels of strength and toughness

that exceed the minimum specified requirements for a titanium hull material; obtaining satisfactory weldments with some of these alloys will be a problem. The usefulness of the DWTT in providing a reliable means of evaluating the results obtained in alloy development, heat treatment, and processing studies has been demonstrated and therefore can be used as a fracture-toughness measurement tool for guiding investigators in these areas.

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